NCAR'S SUMMER COLLOQUIUM

Capacity Building in Cross-Disciplinary Research of Earth System Carbon–Climate Connections

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The Advanced Study Program (ASP) Summer Colloquium is an annual event hosted at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. From its inception in 1966, the summer program was designed to introduce doctoral students from all over the globe to emerging research areas related to the interests of the NCAR community. Its current goal and format is to gather approximately 25 graduate students and similar numbers of renowned scientists in atmospheric and related sciences to delve into a cutting-edge research topic for three weeks. Colloquia themes over the past 10 years have encompassed a broad range of topics, from marine ecosystems and regional biogeochemistry to statistical assessment of extreme weather events and space weather (www.asp.ucar.edu/colloquium/summer_colloquia.php). The colloquia provide an intensive learning experience, and the relationships fostered among participants often persist well beyond the event.

THE NCAR ADVANCED STUDY PROGRAM SUMMER COLLOQUIUM: CARBON–CLIMATE CONNECTIONS IN THE EARTH SYSTEM

WHAT: Twenty-five graduate students and 60 scientists working on the terrestrial and ocean sides of the carbon cycle met to explore research challenges common to both communities.
WHEN: 29 July–16 August 2013
WHERE: Boulder, Colorado

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DOI:10.1175/BAMS-D-13-00246.1

A supplement to this article is available online (10.1175/BAMS-D-13-00246.2)

In final form 20 December 2014

In 2013 the ASP colloquium[1] focused on carbon–climate connections in the Earth system. The choice of the theme was motivated by the observation that the ocean and terrestrial biosphere together absorb about half of the annual anthropogenic emissions of carbon dioxide. Both sinks are sensitive to the

[1] The 2013 colloquium was supported by NCAR ASP through funding from the National Science Foundation.

climate state, and future warming will likely reduce their uptake rates. Furthermore, both sinks depend, at least in part, on the concentration of CO_2 in the atmosphere. However, many uncertainties remain regarding the mechanisms that regulate these natural carbon sinks and feedbacks, which are not easily quantifiable. Achieving a better understanding of those processes is essential to climate prediction and to uncertainty quantification. Earth system models provide a coherent framework in which to represent the mechanisms regulating carbon sinks and their interaction with climate. Ultimately, improving these models will yield more reliable predictions of future climate evolution.

The 2013 colloquium included a researcher workshop during the second week titled "Key Uncertainties in the Global Carbon Cycle: Perspectives across Terrestrial and Ocean Ecosystems." The objectives of the workshop included identifying important, cross-cutting problems in carbon–cycle science common to land and ocean communities. In our opinion one of the major successes of the colloquium was that it provided a unique, and truly interdisciplinary, learning experience for the majority of participants: students, lecturers, and researchers. Here we delve into the lessons learned from this event.

ASP STUDENT ACTIVITIES. The students who took part in the colloquium (names and affiliations are provided in the online supplement: http://dx.doi.org/10.1175/BAMS-D-13-00246.2) were selected from over 120 applicants who had completed at least one year of graduate studies in programs in the United States, Canada, Europe, Asia, and Africa. Half of the students had primary research interests focused on the terrestrial biosphere and the other half on the ocean. The colloquium lecture component introduced the physical, biological, and chemical mechanisms that regulate the global carbon cycle and their representation in Earth system models. The students also participated in hands-on, computer-based tutorials covering Earth system modeling and analytical techniques relevant to carbon cycle science.

Student projects constituted a major component of the colloquium. Groups of four or five students worked to examine aspects of cutting-edge Earth system simulations submitted to phase 5 of the Coupled Model Intercomparison Project (CMIP5) and available through the NCAR computer facilities. Projects were supervised by the lecturers and NCAR scientists, and they covered a range of pressing problems, from developing new metrics to assess the climate model outputs to examining the role of nutrient limitation in the projected terrestrial carbon sink or in the equatorial Pacific Ocean.

THE WORKSHOP. The middle week of the ASP colloquium (6–10 August 2013) consisted of a workshop focused on key uncertainties in global carbon cycle modeling. The workshop[2] brought together 60 terrestrial and ocean carbon cycle scientists from around the world to explore key uncertainties in the global carbon cycle. Its aim was to generate a conversation across traditional disciplinary boundaries to highlight the conceptual challenges common to the two communities while simultaneously introducing the next generation of scientists to the frontier of research. Specifically, the workshop focused on five main topics: global carbon cycle controls, mechanisms that regulate nutrient cycling and their impacts, remineralization pathways, the role of individuals in ecosystem dynamics, and observational data that might constrain carbon cycle feedbacks. Speakers and titles of their presentations are in the online supplement (http://dx.doi.org/10.1175/BAMS-D-13-00246.2).

A round table discussion highlighted if and how research questions with common goals had the potential to be successfully addressed using similar approaches by the two communities. For example, the quantification of the role of extreme but infrequent events in the carbon budget could benefit from parameterizing higher-order statistics in both the terrestrial and the ocean components. Innovative approaches on how to model carbon losses to the atmosphere in terrestrial ecosystems through fire or storms and carbon export to the deep ocean by large sinking particles have the potential to be shared between ocean and land researchers. On the other hand, improvements in the representation of nutrient limitation must follow different trajectories in the two communities due to differences in the relative importance of biological versus physical processes governing the spatial and temporal variability of nutrient cycling.

The workshop identified five major modeling challenges common to the scientific communities

[2] The ASP colloquium workshop was supported by the Carbon Cycle Interagency Working Group, the U.S. National Institute of Food and Agriculture, the Ocean Carbon and Biogeochemistry (OCB) program, and the U.S. Climate Variability and Predictability Program (U.S. CLIVAR).

working on the terrestrial and ocean sides of the carbon cycle, as summarized below.

1) *Remineralization/decomposition.* Microbial respiration is common to land and ocean systems. On land, microbial respiration converts organic carbon and nutrients back to inorganic forms, with a loss of carbon from terrestrial soils and a return of nutrients to bioavailable pools as end results. In the ocean, microbial respiration of sinking organic matter controls the depth of remineralization, which in turn determines the longevity of the carbon sequestration. The dependence of respiration rates on environmental conditions, however, is poorly understood in both systems. Given that the underlying reactions are similar on land and in the ocean, we expect similar responses to changes in analogous environmental variables. The colloquium explored how to circumvent barriers of language, framing of questions, and channeling funding streams in order to develop a transdisciplinary initiative between terrestrial and ocean scientists studying respiration pathways.
2) *Nutrient limitation.* The representation of nutrient limitation in coupled carbon–climate models has followed different paths across the land and ocean communities. In land models, accounting for nutrient limitation is a relatively new challenge and a leading-order source of uncertainty when projecting into the future the terrestrial contribution to carbon uptake. Nutrient limitation is a primary constraint in ocean ecosystem models, although the proportion of different essential elements is still crudely treated. The factors that distinguish nutrient limitation in the ocean from its terrestrial counterpart are a fast biomass turnover rate, fairly strong observational constraints on nutrient cycling, and the homogenization of the marine nutrient reservoir by circulation and mixing. Time scales and substrates differ markedly between the land and ocean; nonetheless, many concepts are transferrable across the two communities. In particular, the workshop highlighted the common need for more observational studies examining the mechanistic controls on nutrient budgets and for a better synergy between modelers and experimentalists to better constrain model formulations through targeted manipulation experiments.
3) *Ecology and physiology.* Terrestrial and marine ecosystems consist of organisms with physiological capacities and constraints; these "traits" determine functional roles, success in competition for resources that limit their growth, and carbon cycling characteristics. The realism of and potential for reliable predictions by ecosystem models is predicated on the accurate understanding and depiction of the feasible trait space. Traits result from resource allocation in the context of finite resources and physiological capacities; therefore, trait space is characterized by trade-offs. A key requirement to developing robust representations of trait spaces lies in accurately understanding physiological trade-offs and the criteria that organisms employ for optimization. Marine and terrestrial ecosystem models have been developed to represent the evolution of a uniformly "seeded" distribution of organisms with different traits that produces a realistic biogeography following local selection processes. The exploration of those models is in its infancy, but they represent a promising tool for examining carbon–climate feedbacks in more biologically mechanistic ways. The workshop emphasized that research on this topic should involve a tighter collaboration between physiologists and modelers. Optimization of traits at both ecological and evolutionary time scales should be considered.
4) *Disturbances and trophic coupling.* Ecosystem structures can be dramatically altered by episodic, rare events. In nonlinear systems, such as our climate or land and marine ecosystems, a forcing exerted intermittently can yield different outcomes than the same integral forcing applied uniformly in time. Mortality rates, for instance, may vary greatly over time in response to sporadic events. Nonetheless, ecosystem models usually represent mortality as a constant loss (in time) proportional to the population density. We need to better understand and quantify the ecosystem responses to disturbances; we also need novel approaches to model processes highly susceptible to disturbance events, like mortality, especially for terrestrial ecosystems given the long response time scales associated with perturbations. Another important source of uncertainty identified at the workshop is provided by the representation of trophic coupling. In marine ecosystems, trophic coupling exerts an important control on phytoplankton biomass and export. Models parameterize such coupling in a rudimentary way and behave dramatically different for subtle parameter changes. We think that improved data constraints for grazing

parameterizations in the ocean through a targeted observational effort should constitute a first-order priority.

5) *Physical climate setting.* In the Earth system modeling framework, carbon cycle models are embedded in global climate models that provide the physical setting. Since many ecosystem processes are sensitive to physical climate variables, it is difficult to attribute specific features of model behavior to a particular component, quantify feedbacks, or disentangle errors and biases. Ecosystem models should therefore be evaluated using suites of different physical settings—to provide better insight into the representation of ecological and physical processes—and climate–carbon feedbacks. There is a clear need for modeling frameworks that permit interoperability of subcomponents. We are not recommending a common coupling infrastructure (e.g., the ability to run an ocean model with different atmospheres), but rather modularity that permits swapping process-level parameterizations. Additionally, it is currently unclear how nonlinear ecosystem responses to physical "disturbances" may alter large-scale carbon distributions. The potential for them to impact the carbon cycle requires that extremes over land (e.g., fires, hurricanes, droughts and floods, heat waves and cold spells) and mesoscale eddies in the ocean are resolved in coupled climate models.

SUMMARY. The organization of such a transdisciplinary colloquium and workshop presented unique challenges. A great deal of effort was spent ensuring that lectures and talks were cohesive and that all speakers identified ways in which their perspective on carbon–climate interactions transcended traditional terrestrial and ocean disciplinary boundaries. By far the best part of the colloquium was the interaction with the strong group of students. A sense of deep curiosity and enthusiasm permeated the event, and personal and professional relationships developed at the colloquium continue to blossom. By exposing students to intense, transdisciplinary training, we hope to have stimulated new ideas that will assist them in the development of cross-disciplinary cooperative research efforts.

The success of this colloquium clearly calls for sustained activities, such as the ASP summer initiatives, to coordinate cross-disciplinary research.

ACKNOWLEDGMENTS. The ASP summer colloquium is generously funded by the National Science Foundation. The workshop was made possible through support from the Carbon Cycle Interagency Working Group, the U.S. National Institute of Food and Agriculture (Grant 11362158), the Ocean Carbon and Biogeochemistry (OCB) program, and U.S. CLIVAR. We wish to thank all the NCAR researchers who contributed to the success of the activity.

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